Identification of $\nu 9/2[404]$ band in ^{97}Sr

J. K. Hwang,[1] A. V. Ramayya,[1] J. H. Hamilton,[1] D. Fong,[1] C. J. Beyer,[1] P. M. Gore,[1] Y. X. Luo,[1,2,3] J. O. Rasmussen,[3] S. C. Wu,[3] I. Y. Lee,[3] C. M. Folden III,[3] P. Fallon,[3] P. Zielinski,[3] K. E. Gregorich,[3] A. O. Macchiavelli,[3] M. A. Stoyer,[4] S. J. Asztalos,[5] T. N. Ginter,[6] S. J. Zhu,[7] J. D. Cole,[8] G. M. Ter Akopian,[9] Yu. Ts. Oganessian,[9] and R. Donangelo[10]

[1]*Physics Department, Vanderbilt University, Nashville, Tennessee 37235*
[2]*Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee 37830*
[3]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[4]*Lawrence Livermore National Laboratory, Livermore, California 94550*
[5]*Massachusetts Inst. of Technology, Cambridge, Massachusetts 11830*
[6]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824*
[7]*Department of Physics, Tsinghua University, Beijing 100084, People's Republic of China*
[8]*Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho 83415*
[9]*Flerov Laboratory for Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Russia*
[10] *Universidade Federal do Rio de Janeiro, Caixa Postal 68528, Rio de Janeiro, Brazil*

(Received 5 February 2003; published 14 May 2003)

An excited rotational band including seven new γ transitions was identified in ^{97}Sr from γ-γ-γ coincidences in the spontaneous fission of ^{252}Cf. This new band, built on the 829.8-keV state, is interpreted as the $\nu 9/2[404]$ rotational band with a very deformed shape. The half-life of the 829.8-keV state is determined to be 265(27) ns in the present work. The new band indicates that the emptying of the upsloping $g_{9/2}$ orbital with $K=9/2$ is closely related to the strong prolate shapes of some bands in the Sr and Zr regions with $A\approx 100$.

DOI: 10.1103/PhysRevC.67.054304 PACS number(s): 21.10.−k, 27.60.+j, 25.85.Ca, 21.60.Cs

In the last three decades, many studies have been done to explore the sudden onset of the high deformation in neutron rich Sr and Zr isotopes with $A\approx 100$ [1]. Generally, we understand that the intruder downsloping $\nu 1h_{11/2}$ orbitals make a big contribution to the high deformation of $\beta_2\approx 0.4$. This idea comes from the experimental observances of the $3/2^-[541]$ and $5/2^-[532]$ rotational bands based on the $\nu h_{11/2}$ orbitals in this region [1]. The $3/2^+$ [411] $\nu 1g_{7/2}$ band in ^{97}Sr has also been observed to be deformed [2,3]. It was reported that the ground and low-lying states in ^{97}Sr are nearly spherical while the $3/2^+$ [411] and $3/2^-[541]$ bands have been observed near 0.6 MeV excitation energy [1–4]. Very recently, the $9/2[404]1\nu g_{9/2}$ band was, for the first time, reported at the excited energy of 1038.8 keV for ^{99}Zr with $N=59$ [5]. From those data, it is thought that the upsloping $9/2[404]$ orbital plays an important role in building the high deformation stability. This position of the $9/2[404]$ band is not consistent with the theoretical shell model calculations that predict a much lower position near the Fermi surface [5,6]. Therefore, other examples of this band will help us illuminate the shell structures of the Sr and Zr nuclei in $A\approx 100$ region. This motivates the present work to find the $9/2[404]$ band in the neighboring ^{97}Sr nucleus with $N=59$. In the present spontaneous fission work of ^{252}Cf, a new band very similar to the previously reported $9/2[404]$ band in ^{99}Zr is identified built on the 829.8-keV isomeric state of ^{97}Sr identified by Monnand *et al.* [7]. We assign this band as the $9/2[404]$ band, which becomes the second observed band in this region.

In the present work, the measurements were carried out at the Lawrence Berkeley National Laboratory by using a spontaneously fissioning ^{252}Cf source inside Gammasphere. A ^{252}Cf source of strength ≈ 62 μCi was sandwiched between two Fe foils of thickness 10 mg/cm^2 and was mounted in a 7.62-cm diameter plastic (CH) ball to absorb β rays and conversion electrons. The source was placed at the center of the Gammasphere array, which for this experiment consisted of 102 Compton suppressed Ge detectors. A total of 5.7×10^{11} triple and higher fold coincidence events were collected. The coincidence data were analyzed with the RADWARE software package [8]. The width of the coincidence time window was about 1 μs.

Partner fragments of ^{97}Sr in spontaneous fission of ^{252}Cf are ^{150}Nd($5n$), ^{151}Nd($4n$), ^{152}Nd($3n$), and ^{153}Nd($2n$). When we set double gates on two known transitions of 167.0 and 140.8 keV belonging to ^{97}Sr, the 522.0 and 205.9 keV transitions are clearly seen in the spectrum. Based on these two transitions, we can identify the six additional new γ transitions. The strongest one of these new transitions feeds the $7/2^+$ state at 307.8 keV. One of the coincidence spectra is shown in Fig. 1. The double gate is set on the new 522.0 transition and the known 167.0 keV transition. Several γ transitions belonging to the partner Nd isotopes as well as the seven other new transitions in ^{97}Sr are marked here. The partial level scheme of ^{97}Sr is shown in Fig. 2. A new rotational band is observed based on the 829.9 keV state. We compared this level scheme with the ^{99}Zr level scheme and found a very similar band with about 10 keV differences. The plots of $E(I)-E(I-1)$ versus I for these two nearly identical bands are shown in Fig. 3. So, from this close similarity, we assign the new band of ^{97}Sr as the $9/2[404]$ rotational band. The spins and parities in this band are assigned based on this configuration.

If this band belongs to the $K=9/2$ configuration, the 829.7 keV state has to be an isomeric state delayed from the

 ©2003 The American Physical Society

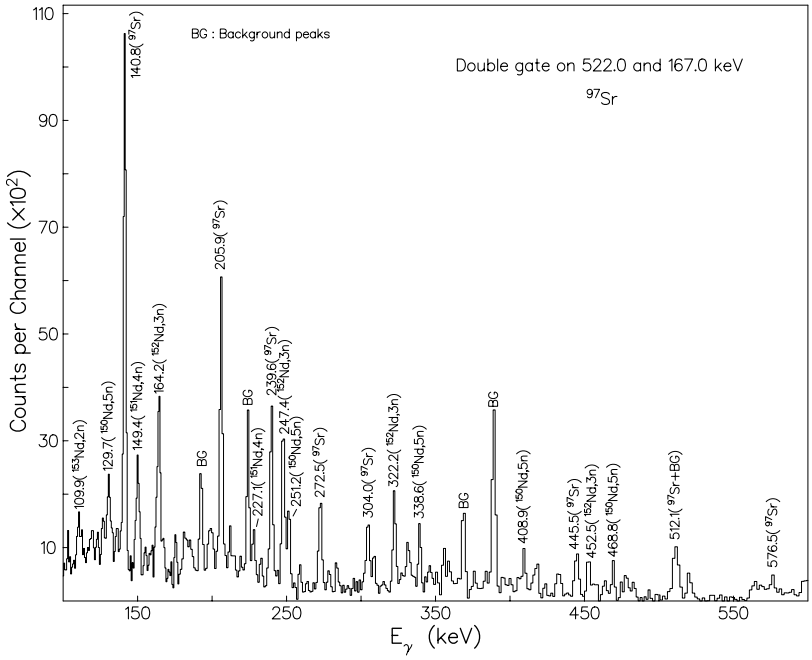

FIG. 1. Coincidence spectrum with double gate set on 522.0 and 167.0 keV transitions in ^{97}Sr.

Weisskopf half-life calculation (T_W) because of the shape difference between the deformed 829.7-keV state ($9/2^+$) and spherical 307.8-keV state ($7/2^+$). In Fig. 4, our coincidence spectra are shown for coincidence time windows of $t=100$, 300, and 500 ns in our cube data of ^{252}Cf. Setting a double gate on the 239.6- and 272.5-keV transitions, the ratios of transition intensities of 205.9 keV (above the 829.8-keV isomeric state) and 522.0 keV (below the 829.8-keV isomeric state) change according to the opening of the coincidence time window (t). The $N(522.0)/N(205.9)$ peak area ratio is proportional to $1-e^{-\lambda t}$, as shown in Fig. 5, from which $T_{1/2}=265(27)$ ns is deduced. This method was checked for the 555.4-keV state of ^{95}Sr (See Figs. 6 and 7) and the result of 23.6(24) ns is in agreement with 21.7(5) ns [9].

The $K=9/2$ bands in ^{99}Zr and ^{97}Sr with $N=59$ have the odd neutron in the $\nu 9/2[404]$ orbital. In the shell model [9–12], for the upsloping $\nu 9/2[404]$ orbital to show up over the Fermi surface at $N=59$ the β_2 value should be around 0.4. This means that this band has a highly deformed prolate shape. The existence of highly deformed shapes at 1038.8 keV in ^{99}Zr and 829.8 keV in ^{97}Sr tells us that the shape coexistence effect prevalent in the Sr and Zr nuclei has to be interpreted by the occupancy competition of three neutron orbitals, $1h_{11/2}$ (downsloping 1/2[550], 3/2[541], and 5/2[532] orbitals), $1g_{9/2}$ (upsloping 9/2[404] orbital), and $1g_{7/2}$ (gently upsloping 3/2[411] orbital), which are all near the Fermi surface in the $\beta_2 \approx 0.3$–0.4 region for $N=58$–60. Then, the high-lying $\nu 9/2[404]$ bands in ^{99}Zr and ^{97}Sr are considered to be unimixed with another band. From the $E2$ and $M1$ transition branching ratios of the states of $13/2^+$, $15/2^+$, and $17/2^+$, the $|g_K - g_R|/Q_0$ (b^{-1}) values were

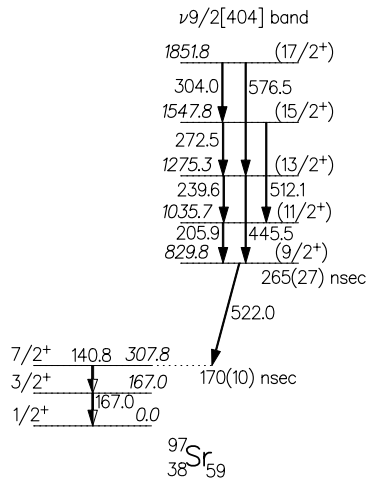

FIG. 2. Partial level scheme of ^{97}Sr. All of the states except the four low lying states are new.

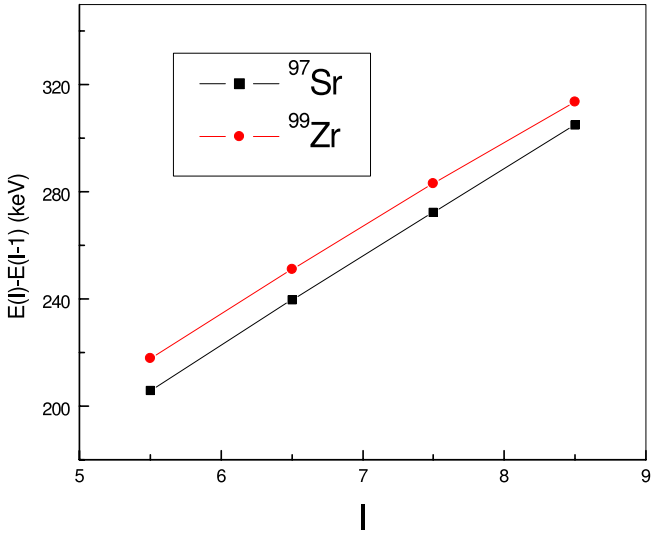

FIG. 3. (Color online) The experimental transition energies of $E(I)-E(I-1)$ versus spin (I) plot in ^{97}Sr and ^{99}Zr showing the close similarity.

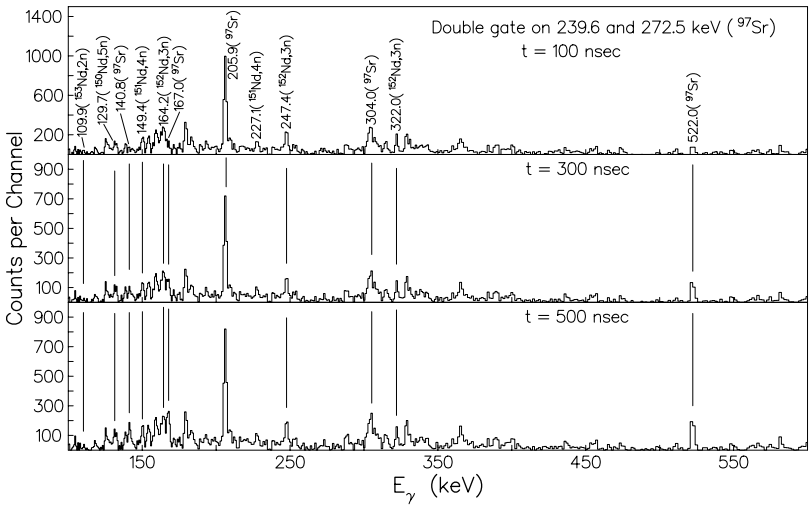

FIG. 4. Coincidence spectrum with double gate set on 239.6 and 272.5 keV transitions with coincidence time windows of $t=100$, 300, and 500 ns in ^{97}Sr.

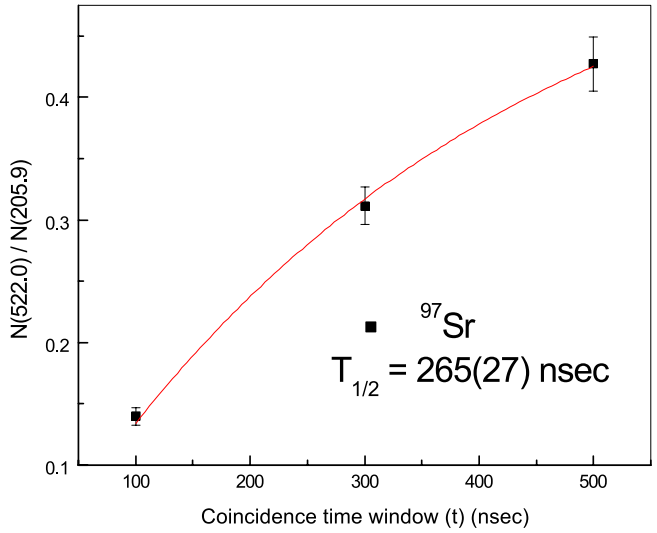

FIG. 5. (Color online) $N(522.0)/N(205.9)$ versus coincidence time window (t) plot. The fitted half-life ($T_{1/2}$) value (solid curve) is 265(27) ns.

obtained as shown in Table I. In the present work, the $|g_K-g_R|/Q_0$ values of ^{97}Sr are compared with those of ^{99}Zr [2] in Table I. Here the prolate shape ($Q>0$) is assumed. The $13/2^+$ and $15/2^+$ states of ^{97}Sr show much bigger values than ^{99}Zr. But for the $17/2^+$ state, ^{97}Sr shows much smaller value than ^{99}Zr. This difference has to be interpreted by the variation of both g_K and Q_0 (intrinsic quadrupole moment) [10,5]. The collective g_R factor is given, in general, by $Z/2A$ for the odd neutron orbital. The intrinsic g_K factor for the Nilson orbital is very sensitive to the change of the nuclear shape parameter and the Nilson shell model parameters for the low K value [10,13]. But the 9/2[404] orbital with high $K=9/2$ value has the constant theoretical g_K value of $g_K=-0.255$ [13,5] if $g_s=0.6g_s(\text{free})=-2.296$. From this theoretical g_K value and the relation of $Q_0=\beta_2 ZA^{2/3}/92.7$ (e b), we can obtain rough β_2 values for each state from Table I. The β_2 values for ^{97}Sr are 0.21(2), 0.24(2), and 0.40(3) for the $13/2^+$, $15/2^+$, and $17/2^+$ states, respectively. The β_2 values for ^{99}Zr are 0.44(3), 0.41(3), and

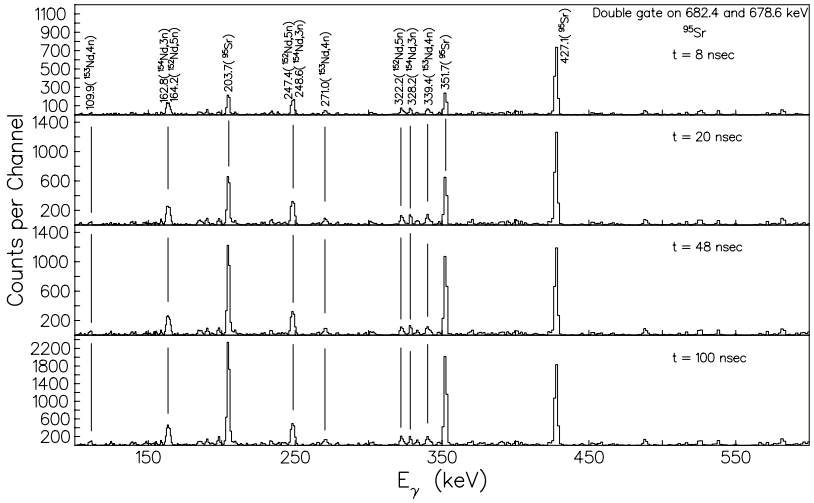

FIG. 6. Coincidence spectrum with double gate set on 682.4 and 678.6 keV transitions with coincidence time windows of $t=8$, 20, 48, and 100 ns in ^{95}Sr.

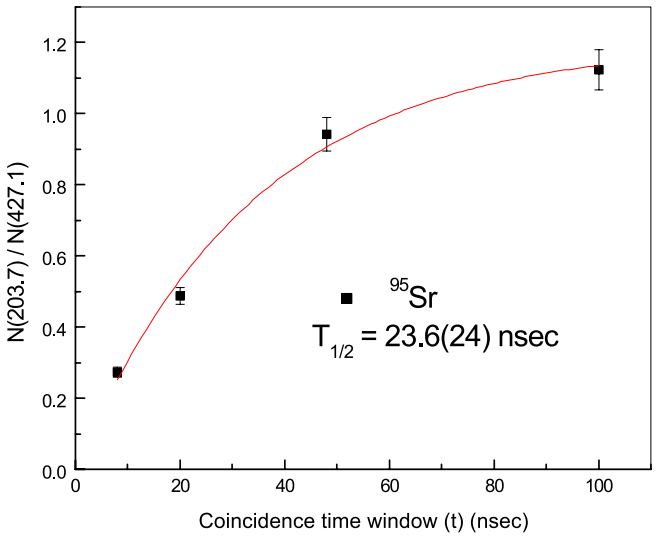

FIG. 7. (Color online) $N(203.7)/N(427.1)$ versus coincidence time window (t) plot. The fitted half-life ($T_{1/2}$) value (solid curve) is 23.6(24) ns which is consistent with the previously observed value of 21.7(5) ns [9].

0.16(6), for the $13/2^+$, $15/2^+$, and $17/2^+$ states [5], respectively. It is not easy to understand smaller β_2 values for the $13/2^+$ and $15/2^+$ states in ^{97}Sr and $17/2^+$ state in ^{99}Zr. If we fix the β_2 values to be about 0.4, the intrinsic g factor (g_K) should be around -0.6 for ^{97}Sr. A high g_K value usually comes from the low K orbitals [5,10,13]. The most probable orbitals with low K values around the Fermi surface with $N=59$ and $\beta_2=0.4$ are $3/2^+$ [411] with $g_K=-0.53$ for ^{99}Sr [7], $3/2^-$ [541], and $1/2^-$ [550]. The g_K value is very sensitive to the shell model parameters [10]. Therefore, mixing with the $3/2^+$[411] orbital might explain, in part, the higher g_k value for the 9/2[404] band. However, the shell model calculation of the g_K value with a little band mixing cannot explain fully the experimental g_K values for $13/2^+$ and $15/2^+$ states in ^{97}Sr and $17/2^+$ state in ^{99}Zr. The 829.8-keV isomeric state with the half-life of 515(15) ns and the spin and parity of $11/2^-$ was reported by Monnand *et al.* [7]. Correcting for an analysis error, their half-life is 255(10) ns [14] to make the two values consistent. The spin and parity of $11/2^-$ was assigned to this isomeric state by Monnand *et al.* [7]. Genevey *et al.* [15] discussed the 1094.1-keV isomeric state in ^{96}Rb and the 829.8-keV isomeric state in ^{97}Sr based on the $\nu h_{11/2}$ configuration with the spherical shape.

TABLE I. Branching ratios and $|g_K-g_R|/Q_0$ (b^{-1}) values in ^{97}Sr and $|g_K-g_R|/Q_0$ (b^{-1}) values in ^{99}Zr [4] in the fifth column.

Level spin	E_γ (keV)	Relative I_γ	$\lvert g_K-g_R\rvert/Q_0$	$\lvert g_K-g_R\rvert/Q_0$ (^{99}Zr) [4]
13/2	239.6(1)	2.86(14)	0.25(2)	0.11(1)
	445.5(1)	1.00(5)		
15/2	272.5(1)	3.00(15)	0.22(2)	0.12(1)
	512.1(1)	1.00(10)		
17/2	304.0(1)	2.95(21)	0.13(2)	0.30(12)
	576.5(1)	1.00(10)		

Then the multipolarity of 522.0-keV transition has to be $M2$ different from the $M1/E2$ multipolarity which is proposed in the present work. Therefore, to explain the band head energy and irregular g_K factors of the 9/2[404] band will require not only more theoretical work but also more detailed measurements of the band properties.

In summary, an excited rotational band including eight new γ transitions was identified in ^{97}Sr from γ-γ-γ coincidences in the spontaneous fission of ^{252}Cf. This new band built on the 829.8-keV state is interpreted as the band head state of the $\nu 9/2[404]$ rotational band with the strong prolate shape. This high hindrance ($\approx 10^6$) of $M1$ or $E2$ decay of this isomeric state could be due to the shape difference. The half-life of the 829.8-keV state is determined to be 265(27) ns. The emptying of the upsloping $g_{9/2}$ orbital with $K=9/2$ is evidently closely related to the large prolate deformation of some bands in the Sr and Zr regions with $A\approx 100$.

The work at Vanderbilt University, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Idaho National Engineering and Environmental Laboratory was supported by U.S. Department of Energy under Grant No. DE-FG05-88ER40407 and Contract Nos. W-7405-ENG48, DE-AC03-76SF00098, and DE-AC07-76ID01570. The Joint Institute for Heavy Ion Research is supported by University of Tennessee, Vanderbilt University, and U.S. DOE through Contract No. DE-FG05-87ER40311 with U. of Tennessee. The authors are indebted for the use of ^{252}Cf to the office of Basic Energy Sciences, U.S. Department of Energy, through the transplutonium element production facilities at the Oak Ridge National Laboratory. The authors would also like to acknowledge the essential help of I. Ahmad, J. Greene, and R. V. F. Janssens in preparing and lending the ^{252}Cf source we used in the year 2000 runs.

[1] J.H. Hamilton, A.V. Ramayya, S.J. Zhu, G.M. Ter-Akopian, Yu.Ts. Oganessian, J.D. Cole, J.O. Rasmussen, and M.A. Stoyer, Prog. Part. Nucl. Phys. **35**, 635 (1995).

[2] G. Lhersonneau, B. Pfeiffer, K.-L. Kratz, H. Ohm, and K. Sistemich, Z. Phys. A **330**, 347 (1988).

[3] M. Buscher, R.F. Casten, R.L. Gill, R. Schuhmann, J.A. Winger, H. Mach, M. Moszynski, and K. Sistemich, Phys. Rev. C **41**, 1115 (1990).

[4] W. Urban, J.L. Durell, A.G. Smith, W.R. Phillips, M.A. Jones, B.J. Varley, T. Rzaca-Urban, I. Ahmad, L.R. Morss, M. Bentaleb, and N. Schulz, Nucl. Phys. **A689**, 605 (2001).

[5] W. Urban, J.A. Pinston, T. Rzaca-Urban, A. Zlomaniec, G. Simpson, J.L. Durell, W.R. Phillips, A.G. Smith, B.J. Varley, I. Ahmad, and N. Schulz, Eur. Phys. J. A **16**, 11 (2003).

[6] G. Lhersonneau, B. Pfeiffer, R. Capote, J.M. Quesada, H. Gabelmann, K.-L. Kratz, and ISOLDE Collabration, Phys. Rev. C

65, 024318 (2002).
[7] E. Monnand, J. A. Pinston, F. Schussler, J. B. Battistuzzi, K. Kawade, H. Lawin, K. Sistemich, and B. Pfeiffer, Annual Report, CEA Grenoble CEA-N-2176, 20, 1980.
[8] D.C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).
[9] *Table of Isotopes*, 8th ed., edited by R. B. Firestone and V. S. Shirley (Wiley, New York, 1996).
[10] H. Mach, F.K. Wohn, M. Moszynski, R.L. Gill, and R.F. Casten, Phys. Rev. C **41**, 1141 (1990).
[11] J. Skalski, S. Mizutori, and W. Nazarewicz, Nucl. Phys. **A617**, 282 (1997).
[12] R.F. Petry, J.D. Goulden, F.K. Wohn, J.C. Hill, R.L. Gill, and A. Piotrowski, Phys. Rev. C **237**, 2704 (1988).
[13] E. Browne and F.R. Femenia, Nucl. Data Tables **10**, 81 (1971).
[14] B. Pfeiffer (private communication).
[15] J. Genevey, F. Ibrahim, J.A. Pinston, H. Faust, T. Friedrichs, M. Gross, and S. Oberstedt, Phys. Rev. C **59**, 82 (1999).